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Determination of the Near-Field-Acoustics of Primary Vehicle Sound Sources in Relation to Indoor Pass-by Noise Testing for the Verification of a Virtual Acoustic Vehicle Model

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ABSTRACT

The exterior sound emission of a vehicle is an increasingly important criterion for the homologation of road vehicles. The latest limit value of 74 dB(A) is already a major challenge for car manufacturers and the EU is planning an even lower limit of 68 dB(A) in the near future. According to DIN ISO 362, the vehicle exterior noise is determined by a standardized procedure – the „Measurement of noise emitted by accelerating road vehicles“, also referred to as outdoor vehicle pass-by.

In this contribution, a new approach for determining the vehicle exterior noise in an early stage of product development is presented. The aim is to transfer the measurements from outdoor testing facilities to acoustic roller test benches and furthermore into an entirely virtual environment. Therefore, a virtual acoustic vehicle prototype is verified and validated by measurements on a roller test bench and on a real test track.

In a first step, a pass-by test series, using a linear microphone array and considering the vehicle as a point source is performed on the acoustic roller test bench of IPEK – Institute of Product Engineering at Karlsruhe Institute of Technology. In order to substantiate the virtual acoustic vehicle model, the contributions of the primary sound sources of the vehicle to the exterior noise have to be investigated, with the objective of a modular approach for the virtual acoustic prototype. For this purpose, the airborne transfer paths between the primary sources and the far-field of the vehicle are determined by reciprocal measurements. Therefore, a dodecahedral speaker applied with white noise is used. Furthermore, the sound pressure levels are measured in the near-field of the primary sound sources – the engine, all four wheels, the exhaust pipe as well as the frontal intake. Using the reciprocally determined airborne transfer paths, the contribution of the sound sources to the sound pressure in far field can be calculated.

Based on the reciprocally determined transfer functions digital filters are computed. The digital filters are convolved with the audio signals which result from the near-field component measurements. Thus the acoustical properties of the vehicle can be reproduced. The processed audio data can be represented in real time by a 5.1 or a wave-field-synthesis framework which is part of a flexible audio-visual stereo projection system (FASP) at the Competence Centre Virtual Reality of Technische Universität Ilmenau.

Index Terms **–** Near Field Acoustics, Simulated Pass-by Noise, Virtual Acoustic Vehicle Model

1. INTRODUCTION

The vehicle development process nowadays contains many different activities, such as the handling of resources, the management of a large amount of information or the adaption to steadily increasing regulatory requirements. Regarding the higher complexity of modern vehicles, influences of particular subsystems on the complete system have to be estimated during the product development already. Therefore, the focus of this contribution is to design a method to support the development process with regard to the homologation of the vehicle exterior noise, in order to prevent necessary modifications of the system in later stages of the development process. Regarding the Noise Vibration Harshness (NVH), this means developing methods, which allow an early identification of the vibro-acoustic influences of the subsystems and their effects on the exterior noise of the complete vehicle.
To achieve this goal, an acoustic virtual vehicle model is developed in a research partnership between the Technische Universität Ilmenau and the Karlsruhe Institute of Technology. The final model will contain a quantification of the dominant sound sources of a vehicle, as well as the acoustic transfer functions from these sources to the potential listening positions of a pedestrian in the far field of the vehicle.
An important procedure for the determination of the exterior noise of a vehicle is the "Measurement of noise emitted by accelerating road vehicles" according to DIN ISO 362-1 [1]. In this standardized procedure, the vehicle is driving on a predefined test track of 20 meters in length and passes two microphones, which are positioned halfway through the test track at a distance of 7.5 m from the longitudinal vehicle axis (Fig. 1).

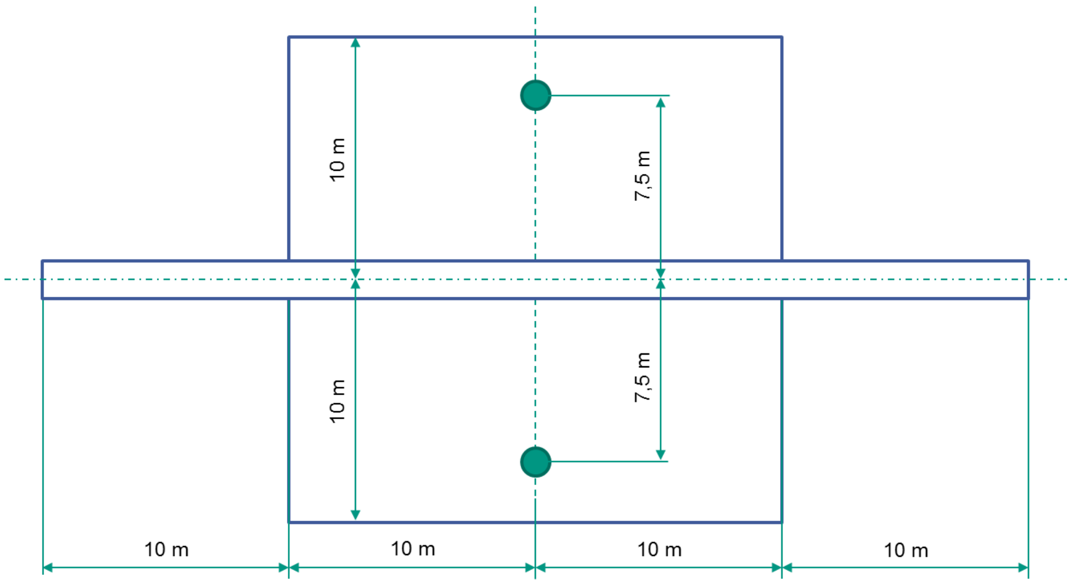

Figure 1: Test track for the pass-by noise measurement

Today's efforts focus on the transfer of this procedure into semi-anechoic chambers with roller test benches – the so called simulated pass-by noise measurement. Therefore, a linear array of microphones is positioned at a 7.5 m distance to the longitudinal axis of the vehicle on a roller test bench [2].

Moreover, the aim is to develop a method that allows a prediction of the pass-by noise level, in an early stage of the vehicle development process, where a complete vehicle prototype does not yet exist. For that purpose, it is necessary to determine the influence of the dominant sound sources of a vehicle on the pass-by noise. It is described with airborne noise transfer functions, as well as the sound pressure level of the sound sources.

With the determined transfer functions, sources can be added or subtracted virtually and the pass-by noise of the complete vehicle or its sub-parts can be auralized and visualized in the flexible audio-visual stereo projection system (FASP) at the TU Ilmenau

1.1 Pass-by noise measurements in context of XiL

For the verification of the development process of a virtual acoustic vehicle model, the X-in-the-Loop (XiL) framework is used [3]. Hereby, the vehicle and its subsystems can be described in a holistic approach. The X represents the system under development (SUD), which can be either a virtual model, or a physical object. It is in constant interaction with the system “Driver” and the system “Environment” with the use of realistic or generic driving maneuvers and test cases. The system “Vehicle” is completed by the rest-vehicle-model, whose level of detail depends on the complexity of the SUD and the chosen validation tasks.

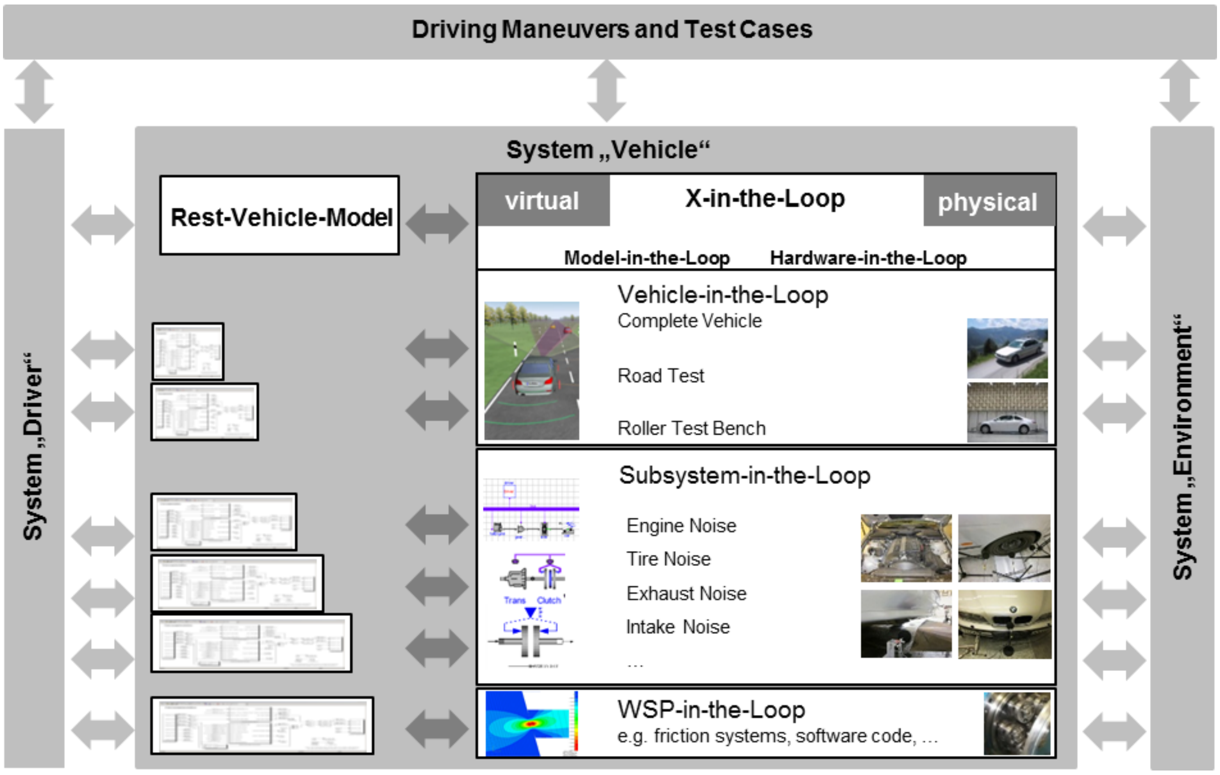

Figure 2: X-in-the-Loop Framework [4]

For the paper at hand, the focus lies on the system “Vehicle” on the Vehicle-in-the-Loop- and the Subsystem-in-the-Loop-level as well as its rest-vehicle-model respectively. Thereby, the simulated pass-by noise is subdivided into the main contributing subsystems and the influence on the complete vehicle is investigated.

2. MEASUREMENTS

In this chapter, the series of measurements for the detailed auralization of a passing vehicle are described. The measurements took place on a roller test bench in a semi-anechoic chamber at the IPEK – Institute of Product Engineering.

2.1 Operational Measurements at the dominant sound sources

For the measurement in use, the vehicle is fixated on the roller test bench and driven at a constant speed of 50 km/h in the second, third and fourth gear. Seven microphones are placed in a distance of 100 mm to the dominant sound sources of the vehicle – the engine, the intake, the exhaust and the four wheels. In the far field, 10 microphones are positioned in a distance of 7.5 m from the longitudinal vehicle axis (Fig. 3).

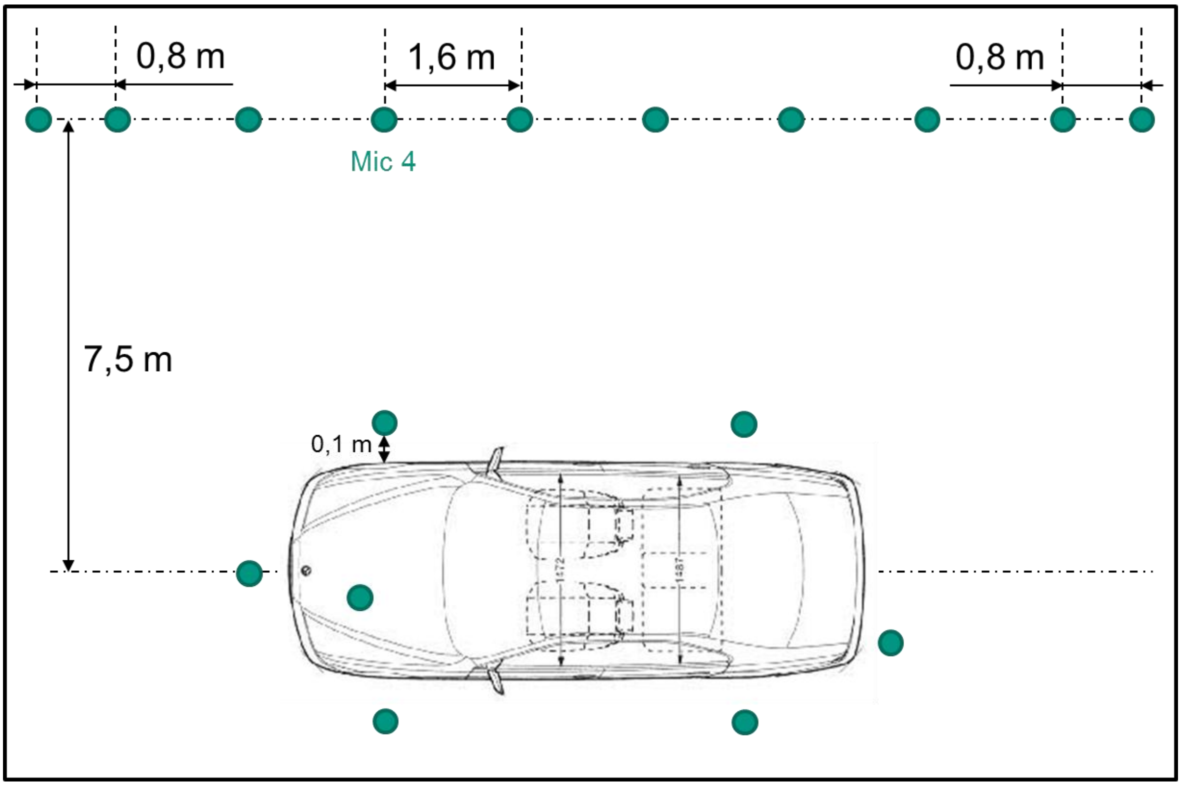

Figure 3: Setup for the simulated pass-by measurement

2.2 Determination of the airborne transfer functions

For the determination of the airborne noise transfer functions from each dominant sound source of the vehicle, to the positions of the linear array microphones for the simulated pass-by in a distance of 7.5 m from the longitudinal vehicle axis, a reciprocal measurement using a dodecahedral speaker is performed.

The pass-by microphones are replaced by the dodecahedral speaker, which is repositioned at every microphone location in the far field step by step. White noise is applied as a source signal. The sound pressure of the dodecahedral speaker has been measured in a setup according to DIN 3744 [5], with the average of 10 microphones on a hemisphere with a radius of 1 m, beforehand.

The emitted noise of the dodecahedral speaker is recorded by the 7 microphones in close proximity to the dominant sound sources, as described in section 2.1.

These measurements provide airborne transfer functions (H) from the respective position of the dodecahedral speaker (a=1 to a=10), to the respective position of the dominant sound source of the vehicle (b=1 to b=7) using the sound pressure.

$$H_{d \to s}^{reciprocal} = \frac{p_{source,b}}{p_{dodecahedron,a}}$$

The test setup is illustrated in Fig. 4.

Figure 4: Measurement setup - reciprocal transfer functions

3. RESULTS

In Fig. 5, transfer functions originating from microphone position 4 (see Fig. 3), are shown exemplary. It can be seen, that the highest damping occurs for the paths to the engine and to the left tires for frequencies above 1000 Hz.

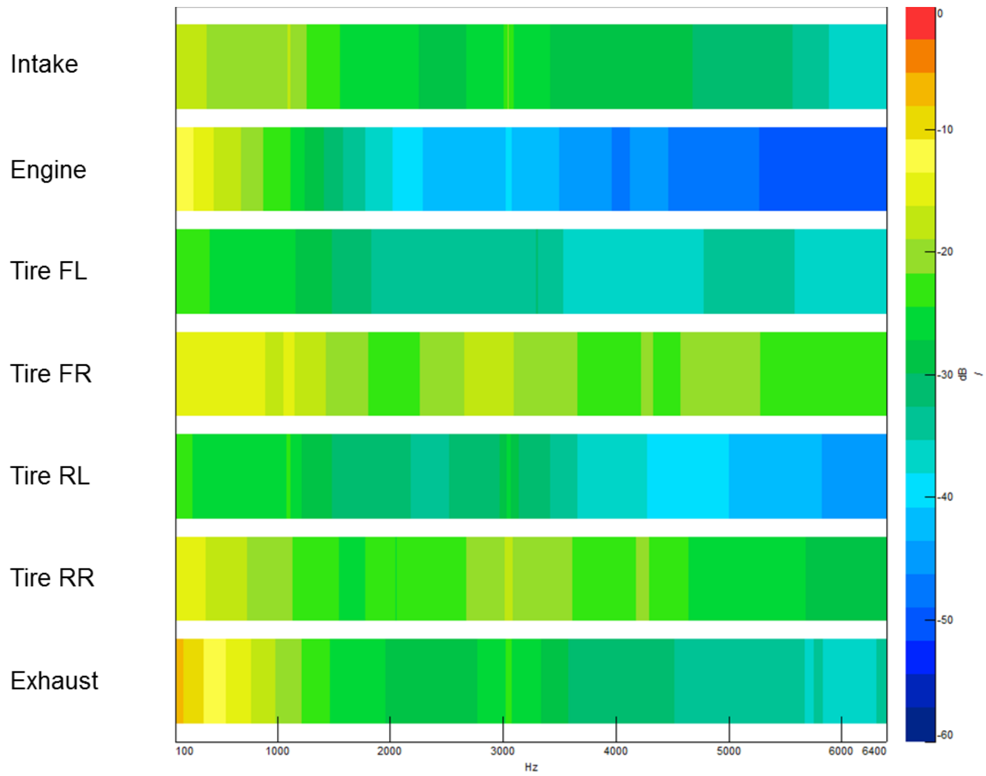

Figure 5: Transfer functions originating from microphone position 4

These functions serve as weighting curves for the audio data of the dominant sound sources, which have been recorded during the operational measurements. By the combination of all 10 microphone positions in the far field, as well as the 7 positions at the vehicle subsystems, a total of 70 transfer functions were determined.

Furthermore, the gathered audio data and transfer functions have been used for an auralization and verification in the FASP at the TU Ilmenau [6]. In a preceding paper, the general feasability of the auralization of the simulated pass-by noise measurement in a FASP has been proven for a complete vehicle [7].

The audio data from each vehicle subsystem, weighted by the transfer functions in the form of digital filters, can be auralized via wave-field-synthesis [8]. With a linear cross-fade between each adjacent microphone in the far field, the noise of a passing vehicle or its subsystems is synthesized.

4. SUMMARY AND CONCLUSION

In the paper at hand, the determination of airborne transfer paths from vehicle subsystems to the measuring position for the simulated pass-by is described. In a first step, an operational measurement is performed, where the emitted noise of the dominant sound sources of the vehicle, as well as the sound of the complete vehicle in the far field are recorded.
In a second step, the airborne noise transfer functions from the sound sources to the measuring position in the far field are determined reciprocally, using a dodecahedral speaker.

These transfer functions are utilized for the calculation of the contribution of each vehicle sound source to the noise in the far field. Applied in the FASP at the TU Ilmenau, the noise of a passing vehicle can be synthesized by crossfading each microphone position in the far field.

Further research should give attention to the analysis of the transfer functions from dominant vehicle sound sources to the far field, using sound intensity measurements. Thereby, transfer paths can be measured independently of the microphone position and distance at the sound sources.

A 3D sound intensity probe can be used to measure the emitted sound intensity of the aforementioned vehicle-parts on a complete vehicle level, as well as on engine test rigs and test rigs for tires, in order to synthesize a complete vehicle noise from different components. The composed noise can then be compared to the measured sound pressure in the far field. Thereby, both methods are validated in regards to the X-in-the-Loop Framework [3].

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